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BLACK VERSUS GRAY T-SHIRTS: COMPARISON OF SPECTROPHOTOMETRIC AND OTHER BIOPHYSICAL PROPERTIES OF PHYSICAL FITNESS UNIFORMS AND MODELED HEAT STRAIN AND THERMAL COMFORT

United States Army
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14. ABSTRACT
This work modeled and compared the heat strain and discomfort differences between black and gray t-shirts. Biophysical properties were measured for 5 ensembles using a sweating thermal manikin. These results showed little differences existed across each of the ensembles, where at 0.4 m/s the ranges were between 0.88 – 0.92 clo and the evaporative potential (im/clo) ranged from 0.51 – 0.54. Spectrophotometric measures differed across the ensembles, where reflection (ρ) 0.24 – 0.49, absorption (α) 0.5 – 0.75, and transmission (τ) 0.01 – 0.04. Predictive modeling showed that heat strain responses were similar for all of the ensembles. While overall the wicking gray shirt had generally better and the wicking black shirt had least favorable values; the differences in impositions to the human are relatively negligible. Similar to the heat strain predictions, modeling for thermal sensation (discomfort) showed very little difference between each of the clothing ensembles. Results support the interest of the Army for purchasing and implementing the replacement of the former gray physical fitness t-shirt with a new black physical fitness t-shirt.

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EXECUTIVE SUMMARY

At the request of Product Manager Soldier Clothing and Individual Equipment (PM SCIE), this program compared the biophysical measures and radiative properties from five physical fitness ensembles. The specific goal was to model and compare the heat strain and discomfort differences between black and gray t-shirts.

Biophysical properties were measured for each ensemble using a sweating thermal manikin. These results showed little differences existed across each of the ensembles, where at 0.4 m/s the ranges were between 0.88 – 0.92 clo and the evaporative potential (i_m/clo) ranged from 0.51 – 0.54. Spectrophotometric measures differed across the ensembles, where reflection ($G_\lambda \rho$) 0.24 – 0.49, absorption ($G_\lambda \alpha$) 0.5 – 0.75, and transmission ($G_\lambda \tau$) 0.01 – 0.04.

Predictive modeling showed that heat strain responses were similar for all of the ensembles. While overall the wicking gray shirt had generally better and the wicking black shirt had least favorable values; the differences in impositions to the human are relatively negligible. Similar to the heat strain predictions, modeling for thermal sensation (discomfort) showed very little difference between each of the clothing ensembles

This work measured and modeled the differences between the biophysical properties and solar properties of five different t-shirt and clothing ensembles. Results from this assessment support the interest of the Army for purchasing and implementing the replacement of the former gray physical fitness t-shirt with a new black physical fitness t-shirt. The currently fielded gray t-shirt and two optional wicking t-shirts were also assessed.

INTRODUCTION

Clothing by design both protects the wearer from environmental threats as well as imposes a level of thermal burden. Both the biophysical resistances (thermal and evaporative) and spectrophotometric (reflectance, absorptivity, and transmittance) properties of clothing can have a significant influence on the impact of the environment on the wearer. To model these impacts on human thermal sensation (e.g., thermal comfort) and thermoregulatory responses (e.g., heat strain), measurements of the biophysical properties and the spectrophotometric measures can be used in mathematical models to simulate responses based on environmental conditions and activities.

At the request of Product Manager Soldier Clothing and Individual Equipment (PM SCIE), a comparison was conducted assessing the thermal impact of five different t-shirts. The PM SCIE request was to conduct biophysical assessments, coupled with modeling and analysis, with the goal of determining whether new black t-shirts absorb more solar radiation than gray t-shirts they replaced, which could potentially increase thermal strain and decrease thermal comfort. Four of the five t-shirts tested were prototypes under consideration; while the fifth t-shirt, the test control, was the formerly fielded gray t-shirt.

METHODS

Standard measurement methods were used to assess both the biophysical properties and spectrophotometric properties of each of the five clothing ensembles and these measured values were input into a thermal sensation model for assessing discomfort and a thermoregulatory model for simulating heat strain.

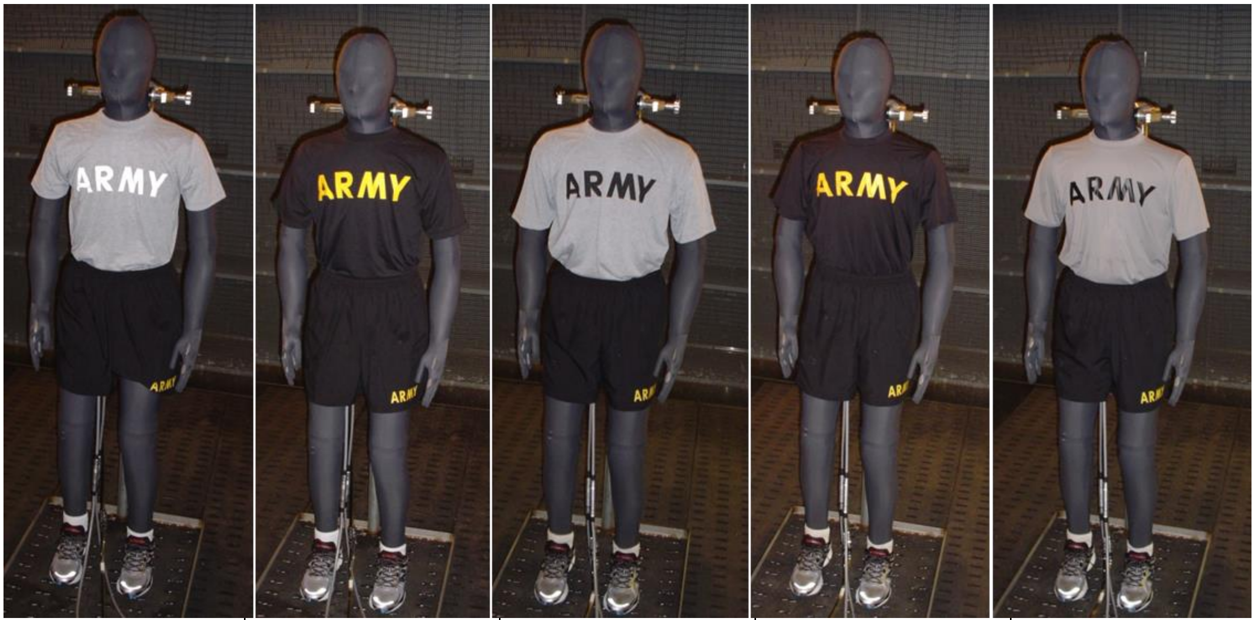
Ensembles

Five exercise ensembles were tested. For each of these configurations, the only difference was the t-shirt; the briefs, shorts, socks, and running shoes were the same in all ensembles (Table 1; Figure 1).

Table 1. Exercise clothing ensembles tested

<table>
<tr><th>Short Title</th><th>T-shirt</th><th>Shorts, socks, running shoes</th></tr>
<tr><td>Control (T0)</td><td>Gray; 100% polyester</td><td rowspan="5">Tan 100% cotton briefs, 100% polyester black shorts, cotton blend crew socks, and New Balance™ running shoes</td></tr>
<tr><td>Current Black (T1)</td><td>Army Physical Fitness Uniform (APFU) Black; 100% polyester</td></tr>
<tr><td>Current Gray (T2)</td><td>Army Physical Fitness Uniform (APFU) Gray; 100% polyester</td></tr>
<tr><td>Wicking Black (T3)</td><td>New Balance™ Black wicking</td></tr>
<tr><td>Wicking Gray (T4)</td><td>New Balance™ Gray wicking</td></tr>
</table>

Figure 1. Physical fitness clothing ensembles assessed



T0 Control	T1 Current black	T2 Current gray	T3 Wicking black	T4 Wicking gray

Biophysical Assessments

Biophysical testing was conducted in a climate controlled wind tunnel using an articulated heated sweating manikin (Newton 20 zone, Thermetrics, LLC, Seattle, WA www.thermetrics.com). Testing was conducted according to American Society for Testing and Materials (ASTM) standards F1291-10 and F2370-10 [1-2] for two biophysical properties, thermal resistance ($R_{ct,}$ m^2K/W) and evaporative resistance ($R_{et,}$ m^2Pa/W).

Thermal resistance (R_{ct}) is the measure of dry sensible heat transfer from the body into the environment, including convection, conduction and radiation. Evaporative resistance (R_{et}) is the measure of heat loss from the body in isothermal conditions ($T_s \approx T_a$); where T_s is surface temperature and T_a is the air temperature. Measurements of R_{ct} are then converted into total insulation (I_T) in units of clo; where 1 clo = 6.45 · I_T [3]; while R_{et} measures are converted to vapor permeability index values (i_m) [4]. A ratio of these two measures, i_m/clo, characterizes the evaporative potential of an ensemble [5].

Key equations for these biophysical measurements include:

$$R_{ct} = \frac{(T_s - T_a)}{Q/A}\,[\mathrm{m^2K/W}] \qquad \text{(Eq 1)}$$

$$R_{et} = \frac{(P_{sat} - P_a)}{Q/A}\,[\mathrm{m^2Pa/W}] \qquad \text{(Eq 2)}$$

$$1\ clo\ =\ 6.45(I_T) \qquad \text{(Eq 3)}$$

$$i_m = \frac{60.6515 \frac{Pa}{°C} R_{ct}}{R_{et}} \qquad \text{(Eq 4)}$$

where T_s is surface temperature and T_a is the air temperature, both in °C or K. Q is power input (W) required to maintain the surface (skin) temperature (T_s) of the manikin at a given set point; A is the surface area of the measurement in m^2; P_{sat} is the vapor pressure in Pascal at the surface of the manikin (assumed to be fully saturated), P_a is the vapor pressure, in Pascal, of the chamber environment.

Spectrophotometric Assessments

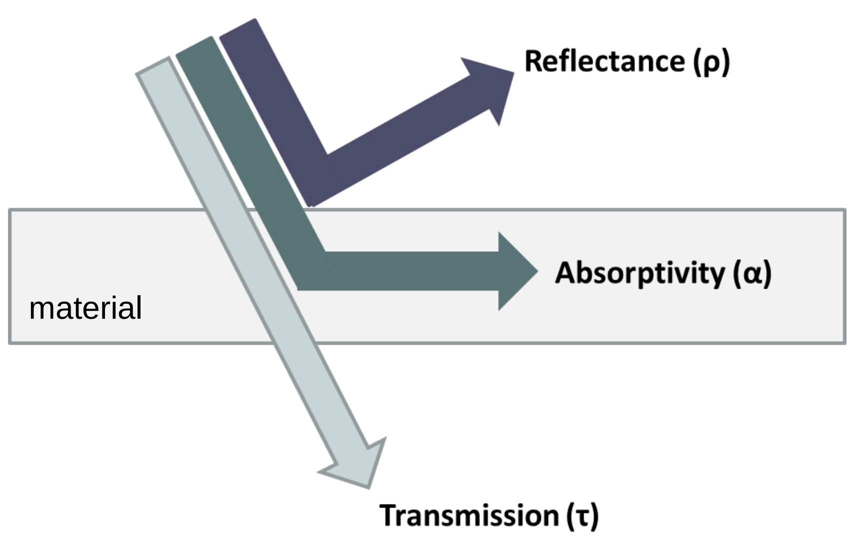
Spectrophotometry measurements were provided by Avian Technologies LLC (Sunapee, NH; http://www.aviantechnologies.com/) and Natick Soldier Research Development and Engineering Center (NSRDEC).

Thermal effects from solar load (i.e., net radiant load) are dependent on the intensity of that load (i.e., radiant flux), clothing properties (i.e., emissivity, absorptivity, transmissivity) and the total area exposed to that given load. The radiant balance can be used to describe the net solar effect; where the net solar balance (G_λ) is a function of reflection ($G_\lambda\rho$), absorption ($G_\lambda\alpha$), and transmission ($G_\lambda\tau$):

$$G_\lambda = G_\lambda\rho + G_\lambda\alpha + G_\lambda\tau \qquad \text{(Eq 5)}$$

Reflection ($G_\lambda\rho$) is radiation redirected back into the environment, absorption ($G_\lambda\alpha$) is absorbed into the material or surface, and transmission ($G_\lambda\tau$) is passed through the material (Figure 2).

Figure 2. Spectrophotometric measures of a material



Key equations for these spectrophotometric measurements include:

$$G_\lambda \rho = \frac{I_\lambda(reflected)}{I_\lambda(incident)} \qquad \text{(Eq 6)}$$

$$G_\lambda \alpha = \frac{I_\lambda(absorbed)}{I_\lambda(incident)} \qquad \text{(Eq 7)}$$

$$G_\lambda \tau = \frac{I_\lambda(transmitted)}{I_\lambda(incident)} \qquad \text{(Eq 8)}$$

where I_λ is the monochromatic intensity of radiation given as a unit of time.

Predictive Modeling

Environment and Activity

Two rates of activity were used, moderate and heavy, for modeling purposes to simulate a slow jog (moderate) and sprinting (heavy rate, e.g., Army Physical Fitness Test - 2 mile run). These two work rates were each modeled at three different environmental conditions. Based on suggested locations, historical data provided by the 14th Weather Squadron of the Air Force Weather Agency (AFWA) was used (Table 2.)

Table 2. Environmental conditions and activity work rates

Location	Symbol	Latitude	Air Temp. (°C)	Dew Point Temp. (°C)	RH (%)	Work Rate
Southeast (Fort Benning)	[1A]	32 N	32.4	23.1	40	Moderate
South (Fort Bliss)	[1B]	32 N	35.5	19.6	58	
Southwest (Yuma, AZ)	[1C]	35 N	39.5	48.9	16	
Southeast (Fort Benning)	[2D]	32 N	30.8	23.1	40	Heavy
Northeast (Fort Drum)	[2E]	44 N	23.7	16.1	62	
Southwest (Fort Irwin)	[2F]	35 N	38.2	6.3	14	

*Each modeled for full sun and wind speeds of 1m/s

Heat Strain

Heat strain predictions were modeled using a modified SCENARIO model [6-7] and a subset of equations from the USARIEM Heat Strain Decision Aid (HSDA) [8-10]. Specific equations included an estimate of the evaporation required for balancing heat (E_{req}), and maximal evaporative capacity (E_{max}), as:

$$E_{req} = M + (BSA \cdot \frac{\bar{T}_{sk} - T_{db}}{R_{ct}}) \qquad \text{(Eq 9)}$$

$$E_{max} = BSA \cdot \frac{P_{s,sk} - RH \cdot P_a}{R_{et}} \text{ (Eq 10)}$$

where *M* is metabolic heat (W), *BSA* is surface area (m^2), $\overline{T}_{sk}$ is the average skin temperature (°C) at the surface, T_{db} is the dry bulb temperature (°C), $P_{s,sk}$ is saturated vapor pressure at the skin temperature (pascal), P_a is vapor pressure (pascal), and RH is relative humidity (%).

Thermal Sensation (TS)

An individual's thermal comfort is generally viewed as a subjective condition. However, it has been shown to have a specific relationship to the environmental conditions, clothing worn, thermal state (e.g., core and skin temperature), and skin wettedness [11-15]. A number of thermal comfort scales exist that predict the mean thermal sensation (TS), e.g., level of discomfort for an individual, given various conditions [13, 16-17]. For this effort, thermal comfort modeling was conducted using a 9 point scale (0-8), where 0 is unbearably cold and 8 is unbearably hot [18]. The predictions were based on core body (T_c) and skin (T_{sk}) temperatures to predict mean TS, using Equation 11:

$$TS = 1.967 * T_c + 0.174 * T_{sk} - 74.841 \quad \text{(Eq 11)}$$

RESULTS

Biophysical Results

Biophysical assessments were conducted according to ASTM standards and additional testing was conducted to determine the wind velocity coefficients [19]. Standard measures of I_T and i_m/clo at 0.4 m/s and at modeling input measures of 1 m/s are shown in Table 3; while wind velocity curves are shown for clo, i_m, and i_m/clo in figures 3-5. From these data we see that, from a biophysical perspective, there is very little difference between each of the ensembles.

Table 3. Total thermal resistance (I_T, clo) and evaporative potential (i_m/clo) at 0.4 m/s (ASTM standard) and 1 m/s (model input)

	Wind Velocity			
	0.4 m/s (Still air)		1 m/s	
	clo	i_m /clo	clo	i_m /clo
Control (T0)	0.88	0.54	0.65	0.74
Current Black (T1)	0.91	0.51	0.65	0.73
Current Gray (T2)	0.92	0.52	0.65	0.73
Wicking Black (T3)	0.91	0.53	0.65	0.74
Wicking Gray (T4)	0.89	0.52	0.65	0.73

Note: lower clo = less thermal resistance, higher i_m/clo = better evaporative potential.

While the test standard for measuring insulation is 0.4 m/s, during active exercise or in outdoor setting, the effective air or wind velocity is generally ≥ 1.0 m/s. Thus there is virtually no real difference in I_T between the 5 ensembles under most conditions.

Figure 3. Thermal resistance (clo) for the 5 ensemble configurations

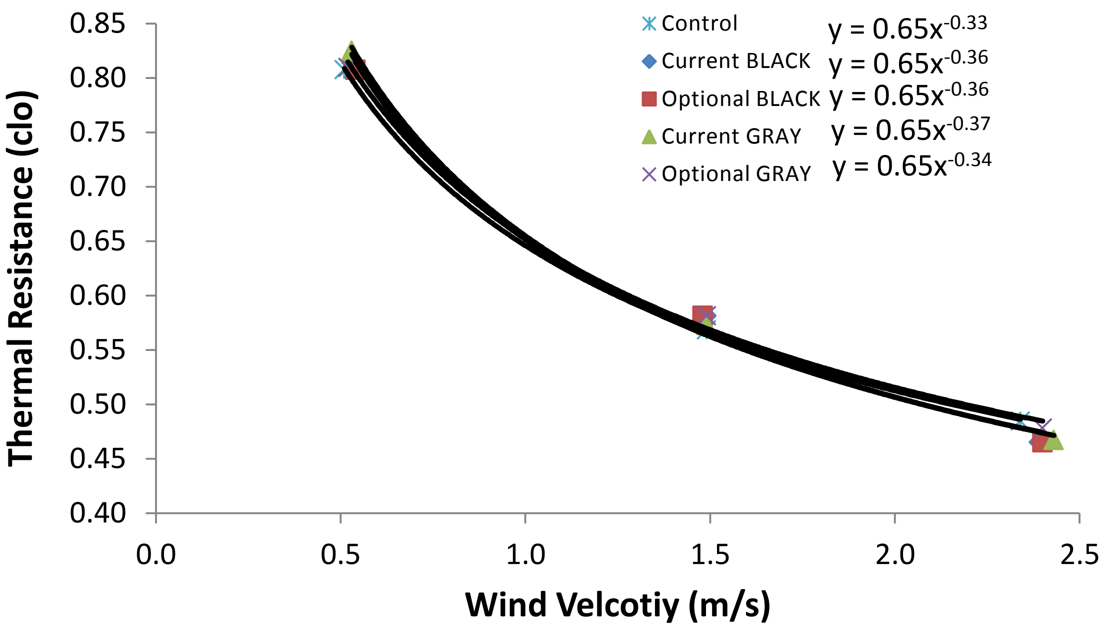


Figure 4. Vapor permeability index (i_m) for the 5 ensemble configurations

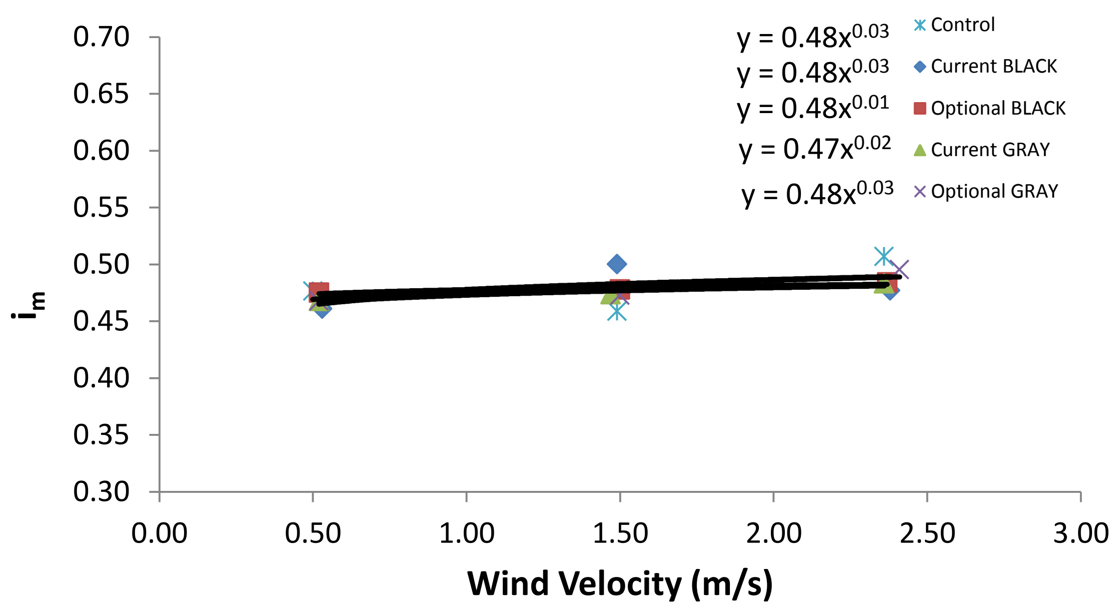
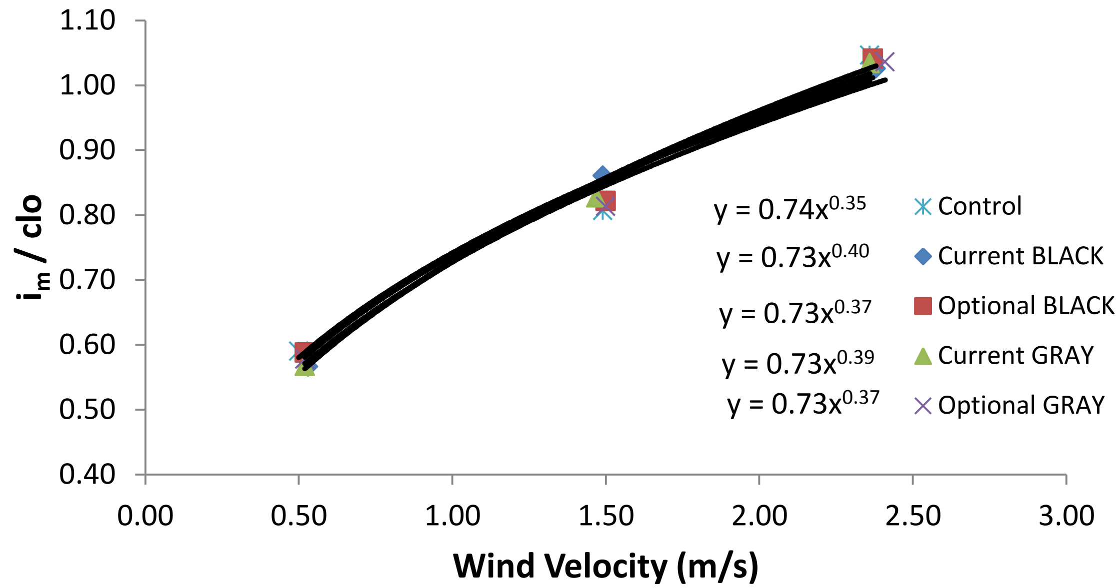


Figure 5. Evaporative potential (i_m/clo) for the 5 ensemble configurations



Spectrophotometric Results

Spectrophotometric measured data of reflection ($G_{\lambda}\rho$), radiation redirected back into the environment, absorption ($G_{\lambda}\alpha$), radiation retained into the material, and transmission ($G_{\lambda}\tau$) of radiation through the material are provided in Table 4.

Table 4. Spectrophotometric measures for the 5 ensemble configurations

Configuration	Reflectance (ρ)	Absorptivity (α)	Transmissivity (τ)	Captured Solar (1-ρ)
Control (T0)	0.25	0.71	0.03	0.75
Current Black (T1)	0.36	0.60	0.04	0.64
Current Gray (T2)	0.24	0.68	0.07	0.76
Wicking Black (T3)	0.24	0.75	0.01	0.76
Wicking Gray (T4)	0.49	0.50	0.01	0.51

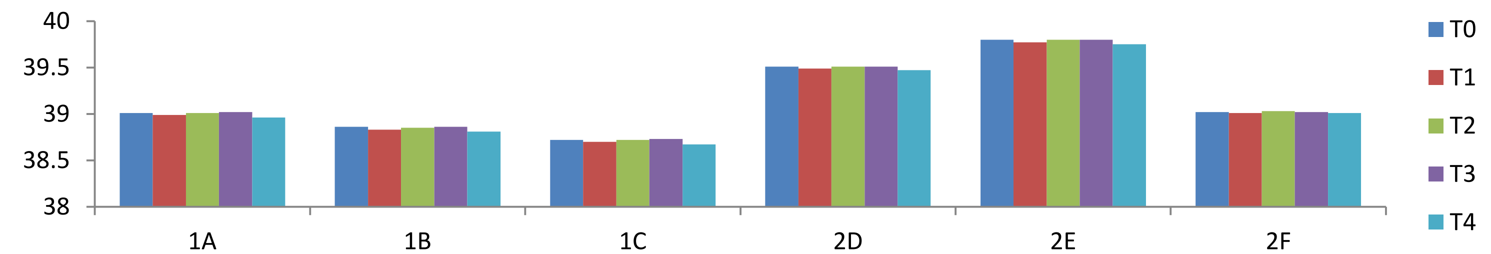
Predictive Modeling Results

Heat Strain

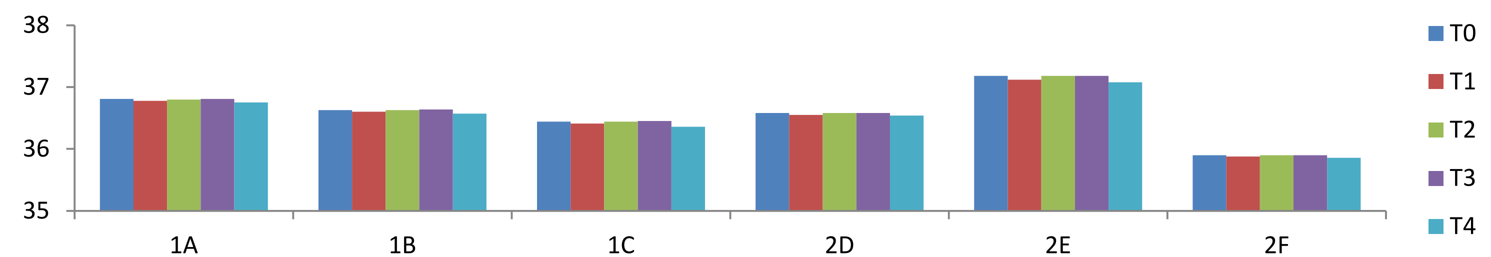
Predictive modeling of the human thermal responses showed relatively similar heat strain between each of the clothing ensembles during both moderate and heavy work conditions (Table 5; Figures 6 and 7). While the wicking gray shirt (T4) tended to be better overall and the wicking black shirt (T3) had the least favorable values; these differences, in terms of their net effect on the human wearers, were negligible.

Table 5. Modeled responses moderate work (~1 hour) and heavy work (2 mile run) in each environmental condition.

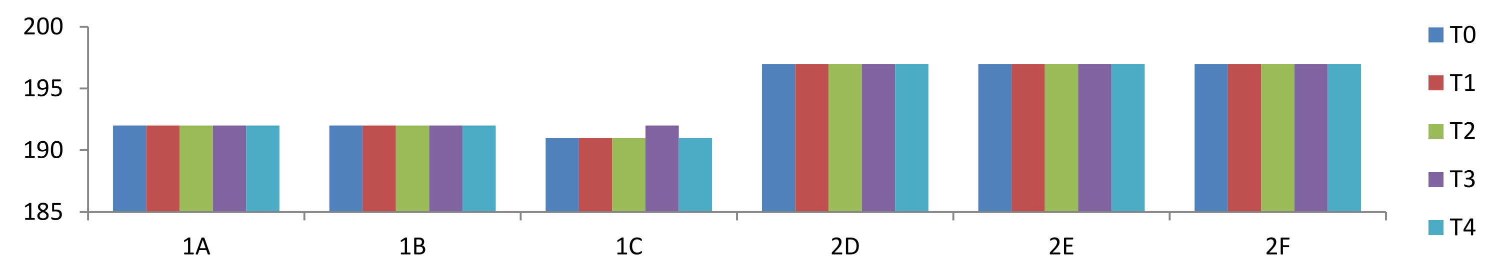
T_c (°C)



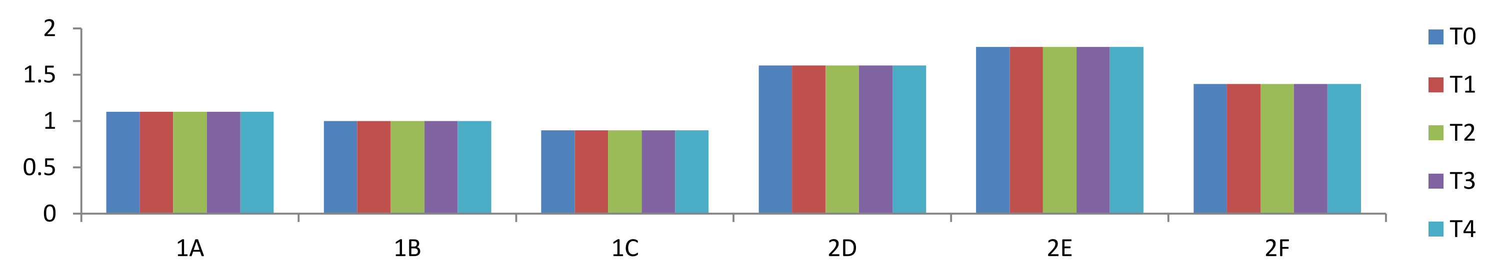
T_{sk} (°C)



HR (bpm)



Sweat Rate (L/h)



1A - Southeast (Fort Benning); 1B - South (Fort Bliss); 1C - Southwest (Yuma, AZ)
2D - Southeast (Fort Benning); 2E - Northeast (Fort Drum); 2F - Southwest (Fort Irwin)

Figure 6. Simulated heat strain via core body temperature (T_c) to each clothing configuration, activity, and environment

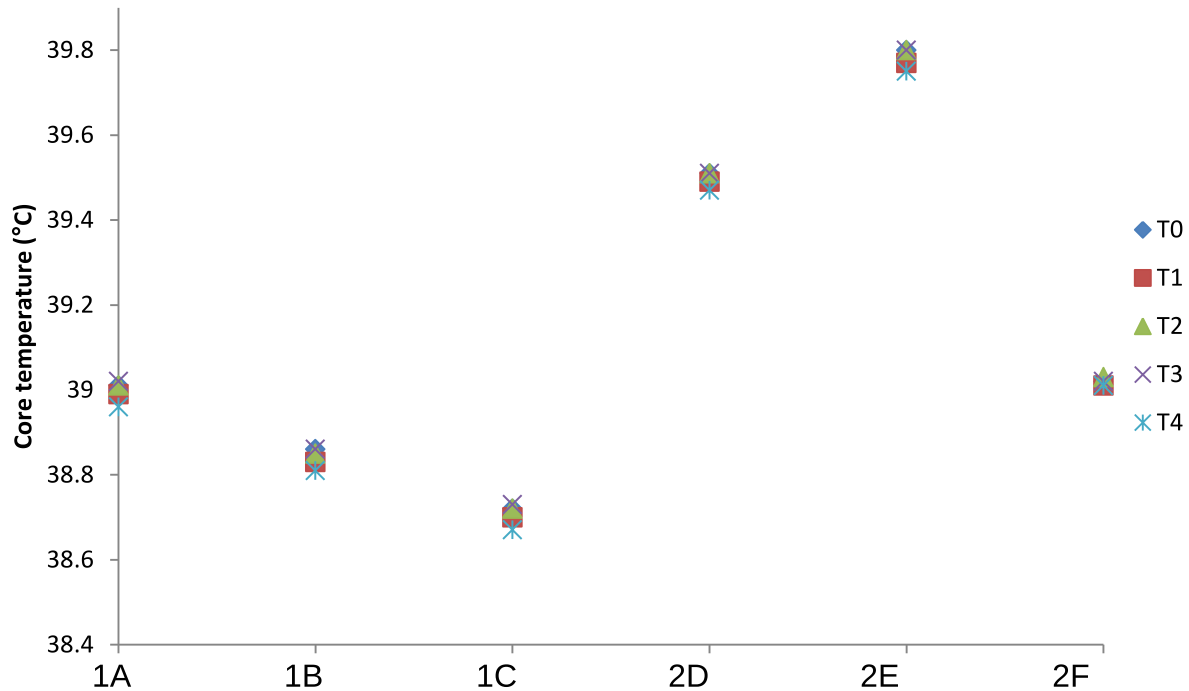
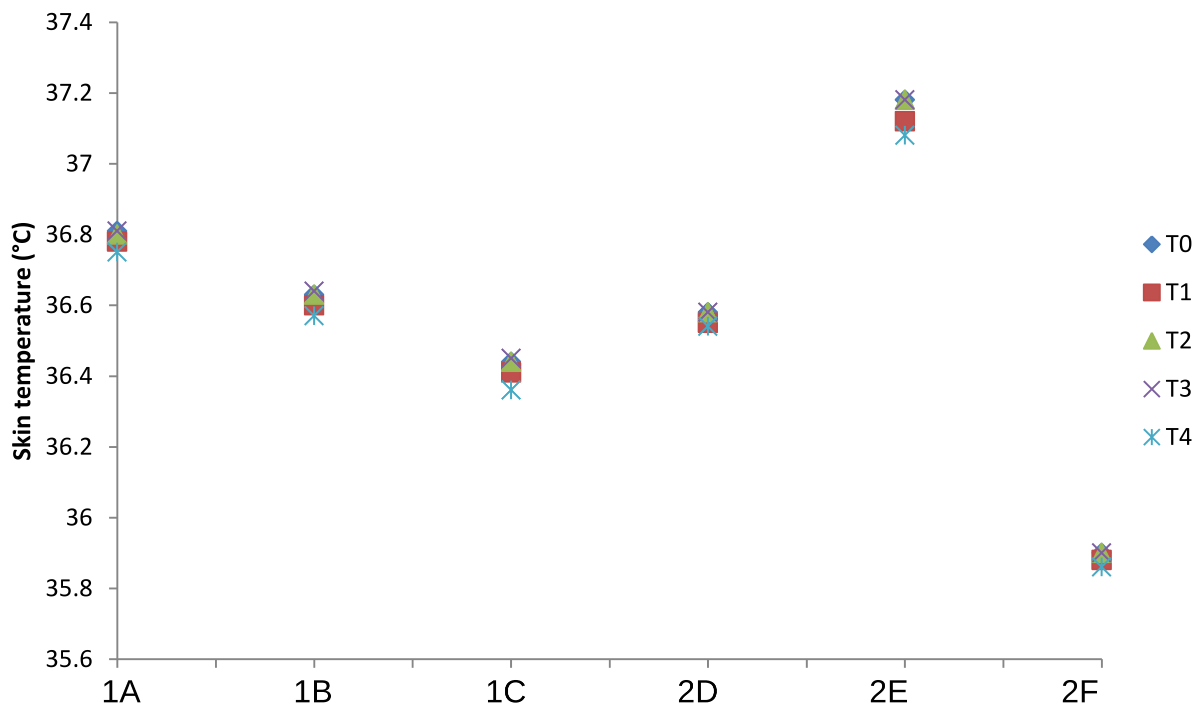


Figure 7. Simulated heat strain via skin temperature (T_{sk}) to each clothing configuration, activity, and environment



1A - Southeast (Fort Benning); 1B - South (Fort Bliss); 1C - Southwest (Yuma, AZ)
2D - Southeast (Fort Benning); 2E - Northeast (Fort Drum); 2F - Southwest (Fort Irwin)

Thermal Sensation (TS)

Similar to the heat strain predictions, modeling for TS (e.g., discomfort) showed very little differences between each of the clothing ensembles (Figure 8; Table 6). As the scale is from 0-8, there were relatively no differences across the higher intensity activity simulations (i.e., 2D, 2E, 2F).

Figure 8. Modeled thermal sensation (TS) for each clothing ensemble within set activity and environmental conditions based on a 9-point (0-8) scale

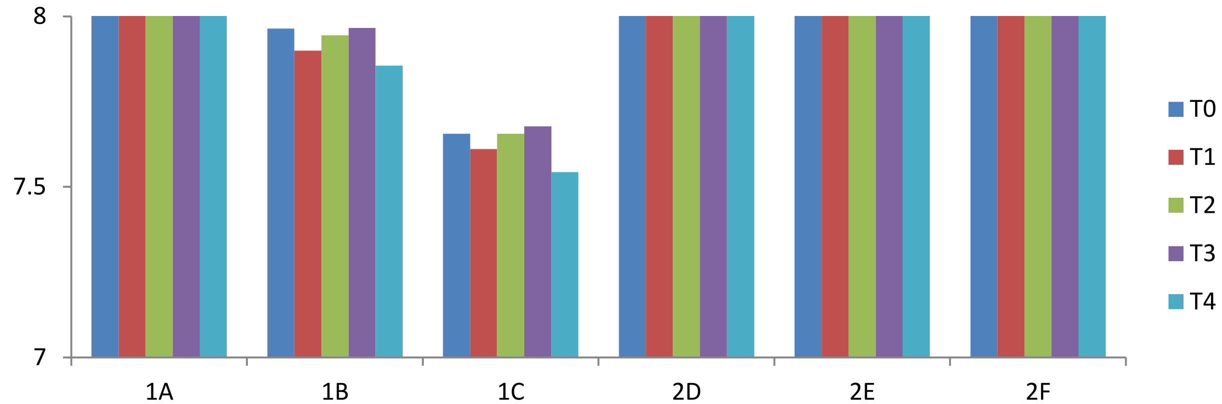


Table 6. Modeled thermal sensation (TS) for each clothing ensemble within set activity and environmental conditions based on a 9-point (0-8) scale

	1A	1B	1C	2D	2E	2F
Control (T0)	>8	8.0	7.7	>8	>8	>8
Current Black (T1)	>8	7.9	7.6	>8	>8	>8
Current Gray (T2)	>8	7.9	7.7	>8	>8	>8
Wicking Black (T3)	>8	8.0	7.7	>8	>8	>8
Wicking Gray (T4)	>8	7.9	7.5	>8	>8	>8

1A - Southeast (Fort Benning); 1B - South (Fort Bliss); 1C - Southwest (Yuma, AZ)
2D - Southeast (Fort Benning); 2E - Northeast (Fort Drum); 2F - Southwest (Fort Irwin)

*Note: The 9-point scale goes from 0-8, therefore all values ≥ 8 should be considered the same

DISCUSSION

These results may be contrary to our intuitive but sometimes erroneous beliefs regarding dark clothing color and solar heat gain, but the results are consistent with more detailed scientific understanding found in the open literature [20-26]. The radiant load includes radiation from near ultraviolet (UV) to the near infrared (IR), not just within the visible spectrum where color is a factor. Incoming radiation that is not reflected is “captured”. Radiation that is transmitted through the clothing is basically unaltered as it passes through the clothing layer, but radiation absorbed into the material may either heat the outer surface of the material or all of the material. It is important to note that the interactions of radiation and clothing are more complex than are discussed in this report. The basic principles and physics of radiation include specific properties of the radiation, including frequency (ν, per/second), wavelength ($\lambda, \mu m$), and wavenumber (λ^{-1}); while the emissions of radiation travel at the speed of light ($\mathcal{C}$), as $\mathcal{C} = * \ \nu$. Therefore, levels of radiant load are also based on the amount of incoming radiation (e.g., from the sun) and the directionality and intensity of the radiation. Full sunlight, even on a clear day, will vary with season, time-of-day and latitude.

The thermal impact of radiant load, including solar radiation, is dependent on the intensity of the radiant load in terms of both the total areas and properties of the exposed surface areas to the radiant load. For an individual wearing an ensemble consisting of shorts and a short-sleeved t-shirt, approximately 29% of the body surface area is covered by the t-shirt, 27% by the shorts, and 44% is uncovered or covered by socks and shoes. Thus any effects related to the different t-shirt will impact less than a third of the effective heat exchange surface area.

The radiant load, including solar load, is dependent on both the intensity of the radiant load and the properties of the exposed surfaces, including the posture and orientation of an individual relative to the radiation sources. Although the full solar spectrum ranges from near ultraviolet to near infrared (300 – 3,000 nm), surface color is only a factor in the visible spectrum, approximately 380 – 780 nm. The non-ionizing radiation is either reflected, absorbed or transmitted. In general, smooth surfaces reflect more radiation, so a smooth material will reflect, or capture less, more radiant energy than a rough or textured surface.

Roller and Goldman [25] modeled various scenarios where the solar heat load imposed onto individuals could be calculated based on location and environment, clothing and/or skin tone, and positioning / posture. With modifications to include known values, these methods are useful in determining the net solar heat load imposed on soldiers within a given set of conditions. Roller and Goldman [25] provided calculations for a number of scenarios and also developed a simplified general equation (Eq 10). Equation 10 calculates the total solar load (R) for the complete incidence of radiation on the human by accounting for the individual's total surface area (A, m^2), non-dimensional ratios for transmission (C), directional intensity of radiation (I), diffuse radiation (D), angles of exposure (γp, P_1, P_2), and albedo (T_{A1}), and the amount of incoming radiation reflected from the ground, as:

$$R = AC(I_{\gamma p} + DP_1 + T_{A1}P_2) \quad [kcal/hr] \qquad \text{(Eq 12)}$$

The underlying equations for each of these key elements of transmitted and absorbed solar loads (direct, diffuse, and reflected ground) from Roller and Goldman [25] were later improved by Breckenridge and Goldman [26]. These improved equations provide predicted and measured values for the incidence of solar load, showing close agreement between measured and calculated values (SD ± 12 W).

From a modeling perspective, estimating total radiation (R_T) can be done using simplified empirical methods [27-28], where R_T can be estimated based on the amount of cloud coverage (x), and amount of energy absorbed (a), in units of metabolic equivalence (METS, where 1 MET = 58.15 W/m^2) (Eq 13). Equation 13 can be simplified to total watts (W) by individual surface area (A, m^2) to:

$$R_T = 4.6(1 - 0.9x) * a\ [METS] \qquad \text{(Eq 13)}$$

$$R_T = A * (4.6 * 58.15(1 - 0.9x) * a)\ \ [W] \qquad \text{(Eq 14)}$$

While it is desirable to have direct measures of clothing properties, they can be often difficult to obtain. To this end, Watanabe et al., [29] provide a table of α values for a number of clothing materials and colors, including black, gray, and white. These reported values for black ranged from 0.61 – 0.97, and from 0.36 – 0.88 for gray; the black values not being consistently higher for black versus gray. The ranges of values in their findings suggest that any assumptions regarding radiant load being based solely on color may be misleading.

When radiation is absorbed, it is usually converted from radiant energy to heat (IR), which may be transferred from the clothing to either the skin surface or the environment. A surface heated by solar radiation may actually create a thermal barrier to heat gain from the environment if air temperature is less than the clothing surface temperature. Multi-layer clothing, especially if it incorporates reflective layers or more open weaves, is a small, but potentially complex dynamic structure that may be distorted by compression, contain moisture under-going phase changes or being absorbed into clothing fibers, air permeability, etc. In addition, surface characteristics of the clothing can alter both emissivity and absorptivity at the clothing surfaces, and may change as the sizing in new clothing is lost during wear and washing. Making assumptions about heat exchange based on clothing color is rather simplistic.

CONCLUSIONS

This work quantified and modeled the differences between the biophysical properties and solar properties of five different t-shirt and clothing ensembles. Results from this assessment helped to inform the Army decision to implement a change in the physical fitness t-shirt from gray to black.

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